Citation for published version:
Wu, D, Rosen, DW, Wang, L & Schaefer, D 2015, 'Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation', Computer-Aided Design, vol. 59, pp. 1-14. https://doi.org/10.1016/j.cad.2014.07.006

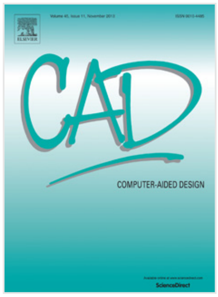
DOI:
10.1016/j.cad.2014.07.006

Publication date:
2015

Document Version
Peer reviewed version

Link to publication

Accepted Manuscript



Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation

Dazhong Wu, David W. Rosen, Lihui Wang, Dirk Schaefer

PII: S0010-4485(14)00156-0
DOI: http://dx.doi.org/10.1016/j.cad.2014.07.006
Reference: JCAD 2229

To appear in: *Computer-Aided Design*

Received date: 8 April 2014
Accepted date: 16 July 2014

Cloud-Based Design and Manufacturing: A New Paradigm in Digital Manufacturing and Design Innovation

Dazhong Wu
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332
Email: dwu42@gatech.edu

David W. Rosen
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332
Email: david.rosen@me.gatech.edu

Lihui Wang
Department of Production Engineering
KTH Royal Institute of Technology
Stockholm 100 44, Sweden
Email: lihuiw@kth.se

Dirk Schaefer*
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332
Email: dirk.schaefer@me.gatech.edu

ABSTRACT

Cloud-based design manufacturing (CBDM) refers to a service-oriented networked product development model in which service consumers are enabled to configure, select, and utilize customized product realization resources and services ranging from computer-aided engineering software to reconfigurable manufacturing systems. An ongoing debate on CBDM in the research community revolves around several aspects such as definitions, key characteristics, computing architectures, communication and collaboration processes, crowdsourcing processes, information and communication infrastructure, programming models, data storage, and new business models pertaining to CBDM. One question, in particular, has often been raised: Is cloud-based design and manufacturing actually a new paradigm, or is it just "old wine in new bottles"? To answer this question, we discuss and compare the existing definitions

for CBDM, identify the essential characteristics of CBDM, define a systematic requirements checklist that an idealized CBDM system should satisfy, and compare CBDM to other relevant but more traditional collaborative design and distributed manufacturing systems such as web- and agent-based design and manufacturing systems. To justify the conclusion that CBDM can be considered as a new paradigm that is anticipated to drive digital manufacturing and design innovation, we present the development of a smart delivery drone as an idealized CBDM example scenario and propose a corresponding CBDM system architecture that incorporates CBDM-based design processes, integrated manufacturing services, information and supply chain management in a holistic sense.

Keywords: Cloud-based design and manufacturing; Collaborative design; Distributed manufacturing; Design innovation; Digital manufacturing.

1. Introduction

In its initial application field of information technology (IT), cloud computing has proven to be a disruptive technology. It leverages existing technologies such as utility computing, parallel computing, and virtualization [1]. Some of its key characteristics include agility, scalability and elasticity, on-demand computing, and self-service provisioning [2]. Adapted from the original cloud computing paradigm and introduced into the realm of computer-aided product development, cloud-based design and manufacturing (CBDM) is gaining significant momentum and attention from both academia and industry. Cloud-based design and manufacturing (CBDM) refers to a service-oriented networked product development model in which service consumers are enabled to configure, select, and utilize customized product realization resources and services ranging from CAE software to reconfigurable manufacturing systems. This is accomplished through a synergetic integration of the four key cloud computing service models: Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a-Service (SaaS) [3]. In order to fully grasp the breadth, depth, and opportunities of CBDM as an emerging paradigm for distributed and collaborative product development [25,64-65], it is advisable

to discuss its two counterparts: cloud-based design (CBD) and cloud-based manufacturing (CBM) separately before shedding more light on how they may act in concert.

Cloud-Based Design (CBD) refers to a networked design model that leverages cloud computing, service-oriented architecture (SOA), Web 2.0 (e.g., social network sites), and semantic web technologies to support cloud-based engineering design services in distributed and collaborative environments [4,25]. Some of the important requirements of a CBD system include (1) it must be cloud computing-based; (2) it must be ubiquitously assessable from mobile devices; and (3) it must be able to manage complex information flow. A detailed requirements checklist for developing CBD systems will be discussed in Section 3. While an ideal CBD system does not yet exist, some companies already develop and provide select critical components for CBD systems. For instance, Autodesk offers a cloud-based platform, Autodesk 123D [5], which allows users to convert photos of artifacts into 3D models, create or edit the 3D models, and generate associated prototypes with remote 3D printers accessed through the Internet. In addition, Autodesk offers a cloud-based mobile application, AutoCAD 360 [6], which allows design engineers to view, edit, and share AutoCAD digital files using mobile devices such as smartphones or tablets. 100kGrarages.com [7], a social network site for connecting consumers with small and medium-sized design companies or individual design engineers, allows a service consumer to search for capable and qualified design service providers in a virtual community by providing consumers with each alternative service provider's profile page. Each profile page includes information such as specialties and sample designs of a service provider.

Cloud-Based Manufacturing (CBM) refers to a networked manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource allocation in response to variable-demand customer generated tasking [8-9]. Table 1 presents another two widely used definitions of CBM. Although each definition may focus on a unique aspect of CBM, they include common elements such as networked manufacturing, ubiquitous access, multi-tenancy and virtualization, big data and the IoT, everything-as-a-service (e.g., infrastructure-

as-a-service, platform-as-a-service, hardware-as-a-service, and software-as-a-service), scalability, and resource pooling.

Table 1. Cloud-based manufacturing-related definitions.

Reference	Definition
[10]	"Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of things (IoT), virtualization and service-oriented technologies, and advanced computing technologies."
[11]	"Cloud manufacturing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction."

Like in the CBD case discussed before, an ideal, fully developed CBM system does not yet exist. Again, a number of companies have started to develop and provide select components for CBM systems. For example, Quickparts [12] is a cloud-based sourcing platform with a focus on low-volume production for custom manufactured rapid prototypes. Quickparts connects service consumers to providers through an instant quoting engine, which transformed sourcing processes from manual to real-time and automatic. Quickparts enables users to upload their CAD data from a variety of commercial CAD software packages such as CATIA and SolidWorks. Based on geometric analysis, Quickparts instantly generates a list of qualified service providers who can manufacture these digital models. Another cloud-based sourcing platform with a focus on high-volume production, LiveSource [13], developed by MFG.com, allows service consumers to have access to request for quotations being sourced by more than 200,000 global service providers. LiveSource enables service consumers to discover and collaborate with quality service providers at shorter deliver times, reduced costs, and a more flexible supply chain. In addition to the two cloud-based sourcing platforms, 3D Hubs [14], a web-based 3D printing platform, helps connect 3D printing service consumers with providers in the local area. According to 3D Hubs, most 3D printer owners use their devices on average less than 10 hours per week. The goal of 3D Hubs is to allow 3D printer owners establish social connections within their local 3D printing community to increase the

utilization of their devices. 3D Hubs has established an innovative business model that creates and delivers value to both 3D printing service consumers and providers. First, each hub, i.e., a 3D printing service provider, decides how much they will charge to 3D print an item. Second, 3D Hubs examines whether a 3D model is watertight using a cloud-based geometric analysis tool [15], conducts printability analysis to verify whether the 3D model is printable, and automatically repair the 3D model if necessary. Third, once the 3D model passes inspection, it will be 3D printed by the hub. 3D Hubs adds a fifteen percent on top of the original quote.

As stated before, CBDM is a decentralized and networked design and manufacturing model based on many enabling technologies such as cloud computing, social media, the Internet of Things (IoT), and service-oriented architecture (SOA), all of which form the backbone of this new design and manufacturing paradigm. An ongoing debate on CBDM revolves around several aspects such as definitions, key characteristics, computing architectures, programming models, file systems, operational processes, information and communication models, and new business models pertaining to CBDM. Although a few definitions for CBM have recently been proposed, they are not yet commonly accepted. Moreover, some prototype systems have been developed and are being tested in industry; however, whether or not these prototypes are truly CBDM systems remains a question. Thus, to gain a better understanding of CBDM, a thorough comparison between CBDM and other relevant design and manufacturing systems is required.

The primary objective of this paper is to answer the following question: Can cloud-based design and manufacturing (CBDM) be considered a new, emerging paradigm in design innovation and digital manufacturing as we would like to argue, or is it just old wine in new bottles? The secondary research objective is to propose a generic CBDM system architecture that describes how currently existing cloud-based design and manufacturing services can be integrated and what new services and technologies should be developed to realize our vision of the factory-of-the-future. In order to achieve these objectives, we proceed as follows. Section 2 introduces the evolution of design and manufacturing systems, including centralized and decentralized design and manufacturing systems. Section 3 introduces key characteristics

of CBDM and presents a requirements checklist that CBDM systems should satisfy. Section 4 compares and contrasts CBDM with other distributed design and manufacturing systems. Section 5 presents a generic CBDM system architecture based on which a smart delivery drone is developed. The drone example is meant to further clarify the CBDM concept and demonstrate how to implement CBDM. Section 6 draws conclusions that finally answer the question initially posed.

2. Evolution of design and manufacturing systems

2.1 Engineering design

Engineering design is a social and technical process in which products are designed by teams of people in single or multiple companies. Many researchers have proposed descriptive models that abstract the engineering design process. Among these models, one of the most widely known is perhaps the one proposed by Pahl and Beitz. It presents a systematic engineering design approach including four core design phases: product planning and clarifying the task, conceptual design, embodiment design, and detail design [16]. Similarly, Ulrich and Eppinger [17] introduce a more refined design process by incorporating prototype testing, refinement, and production ramp-up into the original Pahl and Beitz approach. Since these two well-accepted design approaches were first proposed and later on become common design practice in industry, many similar models based on a similarly linear sequence of design phases have been proposed. Interestingly, almost all of these models represent incremental variations or modifications of the before-mentioned two original based models [18-20].

In addition to systematic design processes, product design also needs to be facilitated by computer-aided systems to assist designers in the creation, analysis, and optimization of a design. Design engineers have used Computer-Aided Design (CAD) systems to design products since the 1960s. Table 2 briefly summarizes key milestones of the evolution of computer-aided design from centralized standalone systems, to distributed web-based systems, and finally to CBD. It is argued that the first CAD system, SKETCHPAD, was developed at MIT by Ivan Sutherland in the early 1960s [21]. SKETCHPAD was a

centralized standalone system which consisted of a large and at the time expensive computer with 306 kilobytes of core memory, an oscilloscope display screen, a light pen for input, and a pen plotter for output [22]. The first commercial applications of CAD systems were found in large enterprises, mainly in the automotive and aerospace industries. Back then, those were the only ones who could afford and justify the extremely high operation and maintenance costs of the early-day CAD systems. With the advancement of computer hardware and geometric modeling, CAD systems could be run on more affordable personal desktop computers and allowed for 3D solid modeling. With the advancement of the Internet and the client-server model, distributed CAD and the sharing of decentralized computing resources became possible. Later on, web-based CAD system based on the thin server-strong client architecture turned out to be hard to implement because of the heavy-weighted client mechanism; however, CAD systems based on the strong server-thin client architecture model are more effective and efficient in distributed and collaborative settings because of their light-weighted client mechanism [23-25,64-65]. One of the latest technological advancements related to computer-aided product development, often referred to as cloud-based design (CBD), started to emerge at the beginning of the 2010s. Because of the inherent characteristics of CBD systems as stated before based on cloud computing, virtualization, multi-tenancy, ubiquitous access, software-as-a-service, pay-per-use business model, and so on, it has the potential to become a game changer for the next generation distributed and collaborative design. In this paper, we focus on the system/tool-related aspects of engineering design as opposed to the design process itself. A discussion of the potential impact of CBD on the design process itself in the broader context of social product development deserves a separate paper [26-27].

Table 2. Evolution of computer-aided design systems.

Time	Configuration	Characteristics
1960s	Centralized	Standalone system; Operate on large and expensive computers; Generate 2D drawings with a light pen on a CRT monitor;
1970s	Centralized	Standalone system; Operate on affordable personal desktop computers; Perform 3D solid modeling;
1980s	Distributed	Thin server + strong client;

		Heavy-weighted client mechanism; Hard to be implemented on the Internet;
1990s	Distributed	Strong server + thin client; Light-weighted client mechanism; Adopt the application service provider (ASP) model Easy to be implemented on the Internet;
Beyond 2010s	Distributed	Cloud computing-based; Virtualization; Multi-tenancy; Social media; Ubiquitous access; Software-as-a-Service; Pay-per-use;

2.2 Manufacturing systems

Similar to design systems, manufacturing systems have undergone a number of major transitions due to changing market demands and emerging technologies [28-29]. Table 3 shows a brief evolution of manufacturing paradigms from the assembly line, to Toyota production systems (TPSs), to flexible manufacturing systems (FMSs), to reconfigurable manufacturing systems (RMSs), to web- and agent-based manufacturing systems, and finally to CBM.

Table 3. Evolution of manufacturing systems.

Time	Systems	Configuration	Characteristics
1900s	Assembly line	Centralized	Reduced labor costs; Increased production rate;
1960s	Toyota production systems	Centralized	Reduced waste of over production; Reduced waiting time; Reduced defective products; Continuous improvement;
1980s	Flexible manufacturing systems	Centralized	Reduced inventories; Improved productivity; Increased system reliability; Increased variety of parts; Improved machine utilization; Improved response to engineering changes;
1990s	Reconfigurable manufacturing systems	Centralized	Increased responsiveness to market changes; Reduced time required for product changeover; Reduced lead time for launching new manufacturing systems; Rapid integration of new technology;

2000s	Web-based and agent-based manufacturing systems	Distributed	Improved information sharing; Improved resource reuse; Improved computational performance; Remote monitoring and control;
Beyond 2010s	Cloud-based manufacturing systems	Distributed	Rapid capacity scalability; Reduced time-to-market; Reduced costs; Ubiquitous computing environment; Pooled manufacturing resources; Improved information sharing; Improved resource reuse; Improved machine utilization;

For example, Henry Ford created the first assembly line, in which interchangeable parts can be added to a product in a sequential manner to produce finished products more efficiently and cost-effectively. In the 1960s, to reduce manufacturing costs, TPSs, also known as just-in-time production systems, were devised. TPSs are characterized by a number of principles that assist in eliminating waste by reducing waiting time, inventory, and the number of defective products. In the 1980s, to yield new product variants, FMSs were developed, allowing for a high degree of functional flexibility. Specifically, the major advantage of an FMS is that it allows for variation in both parts and assemblies; however, its implementation is usually costly. According to Koren et al., “in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements, reconfigurable manufacturing systems (RMSs) are designed at the outset for rapid change in structure, as well as in hardware and software components” [30]. The key features of RMS include modularity, integrability, customization, convertibility, and diagnosability [31].

The previously stated manufacturing systems fall into the category of centralized manufacturing with significant changes in machine tools, manufacturing plant layouts, and business models. With the development of the Internet, distributed manufacturing systems have been increasingly adopted by industry; two major approaches for distributed manufacturing are web- and agent-based manufacturing systems. Web-based systems use the client-server architecture with the Internet to provide a light-weight platform for geographically dispersed teams to access and share manufacturing-related information via a web browser [25,32]. Likewise, with the increasing structural and functional complexity of web-based

manufacturing systems, agent-based manufacturing systems aim at improving computational performance and communication using agents [33-34]. Agent-based manufacturing systems consist of agents (e.g., manufacturing cells, machine tools, and robots) exhibiting autonomous and intelligent behavior such as searching, reasoning, and learning. For example, an agent is an independent problem-solver capable of making decisions by interacting with other agents and its environment [35].

3. Characteristics and requirements for cloud-based design and manufacturing systems

According to the existing definitions for CBDM presented in Section 1, Table 4 lists some common key characteristics of CBDM and compares CBDM with other relevant distributed design and manufacturing systems. As shown in Table 4, CBDM provides significantly more benefits than web- and agent-based systems.

Table 4. Key characteristics and comparison.

Characteristics	Web-based	Agent-based	Cloud-based
Scalability	X	X	X
Agility	X	X	X
High performance computing		X	X
Networked environment		X	X
Affordable computing			X
Ubiquitous access			X
Self-service			X
Big data			X
Search engine			X
Social media			X
Real-time quoting			X
Pay-per-use			X
Resource pooling			X
Virtualization			X
Multi-tenancy			X
Crowdsourcing			X
Infrastructure-as-a-service			X
Platform-as-a-service			X
Hardware-as-a-service			X
Software-as-a-service			X

Table 5. A requirements checklist for CBDM systems.

Requirement	Requirement description

R1.	Should provide social media to support communication, information and knowledge sharing in the networked design and manufacturing environment
R2.	Should provide cloud-based distributed file systems that allow users to have ubiquitous access to design- and manufacturing-related data
R3.	Should have an open-source programming framework that can process and analyze big data stored in the cloud
R4.	Should provide a multi-tenancy environment where a single software instance can serve multiple tenants
R5.	Should be able to collect real-time data from manufacturing resources (e.g., machines, robots, and assembly lines), store these data in the cloud, remotely monitor and control these manufacturing resources
R6.	Should provide IaaS, PaaS, HaaS, and SaaS applications to users
R7.	Should support an intelligent search engine to users to help answer queries
R8.	Should provide a quoting engine to generate instant quotes based on design and manufacturing specification

Based on the key characteristics listed in Table 4, we have developed a requirements checklist that an idealized CBDM system should satisfy (see Table 5). The purpose of the requirements checklist is to clearly define whether or not a given design and manufacturing system falls into the realm of CBDM. Each requirement is detailed as follows:

- Requirement 1 (R1): To connect individual service providers and consumers in a networked design and manufacturing setting, a CBDM system should support social media-based networking services. Social media applications such as Quirky allow users to utilize/leverage crowdsourcing processes in design and manufacturing. In addition, social media does not only connect individuals; it also connects design- and manufacturing-related data and information, enabling users to interact with a global community of experts on the Internet.
- Requirement 2 (R2): To allow users to collaborate and share 3D geometric data instantly, a CBDM system should provide elastic and cloud-based storage that allows files to be stored, maintained, and synchronized automatically.
- Requirement 3 (R3): To process and manage large data sets, so called big data, with parallel and distributed data mining algorithms on a computer cluster, a CBDM system should employ an open-source software/programming framework that supports data-intensive distributed

applications [36]. For example, MapReduce is one of the most widely used programming models in cloud computing environments, as it is supported by leading cloud providers such as Google and Amazon [37].

- Requirement 4 (R4): To provide SaaS applications to customers, a CBDM system should support a multi-tenancy architecture. Through multi-tenancy, a single software instance can serve multiple tenants via a web browser. According to Numecent [38], a cloud platform, called Native as a Service (NaaS), is developed to deliver native Windows applications to client devices. In other words, NaaS can "cloudify" CAD/CAM software such as Solidworks without developing cloud-based applications separately. With such a multi-tenant platform, such programs can be run as if they were native applications installed on the user's device.
- Requirement 5 (R5): To allocate and control manufacturing resources (e.g., machines, robots, manufacturing cells, and assembly lines) in CBDM systems effectively and efficiently, real-time monitoring of material flow, availability and capacity of manufacturing resources become increasingly important in cloud-based process planning, scheduling, and job dispatching. Hence, a CBDM system should be able to collect real-time data using IoT technologies such as radio-frequency identification (RFID) and store these data in cloud-based distributed file systems.
- Requirement 6 (R6): To implement a service-oriented architecture model in design and manufacturing, a CBDM system should provide for users X-as-a-service (everything as a service) applications such as IaaS, PaaS, HaaS, and SaaS.
- Requirement 7 (R7): To assist users to find suitable manufacturing resources in the cloud, a CBDM system should provide an intelligent search engine for design and manufacturing to help answer users' queries [39].
- Requirement 8 (R8): To streamline workflow and improve business processes, a CBDM system should provide an online quoting engine to generate instant quotes based on design and manufacturing specifications.

4. Comparing cloud-based with web- and agent-based design and manufacturing

In addition to the comparison presented in Section 3, the differences and similarities between CBDM and web- and agent-based systems will be articulated from a number of perspectives, including (1) computing architecture, (2) data storage, (3) sourcing process, (4) information and communication infrastructure, (5) business model, (6) programming model, and (7) communication.

4.1 Computing architecture

From a computing perspective, the difference between web- and agent-based applications and cloud-based applications is two-fold: multi-tenancy and virtualization. Fig. 1 illustrates a unified computing architecture for CBDM systems that is distinguished from web- and agent-based design and manufacturing systems.

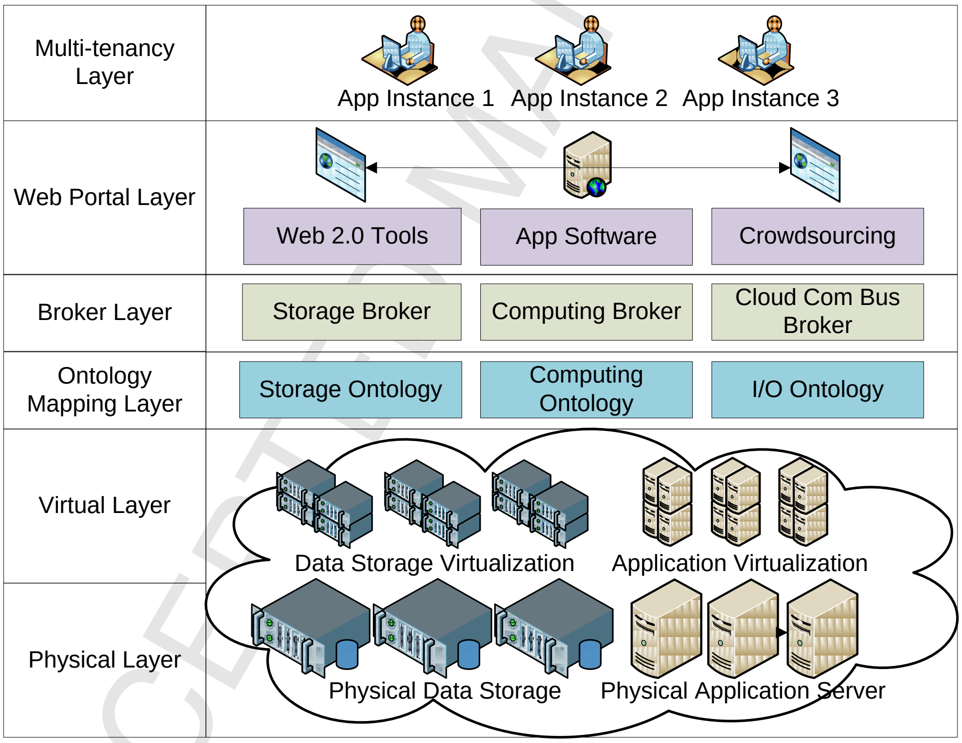


Fig.1: A computing architecture for CBDM systems.

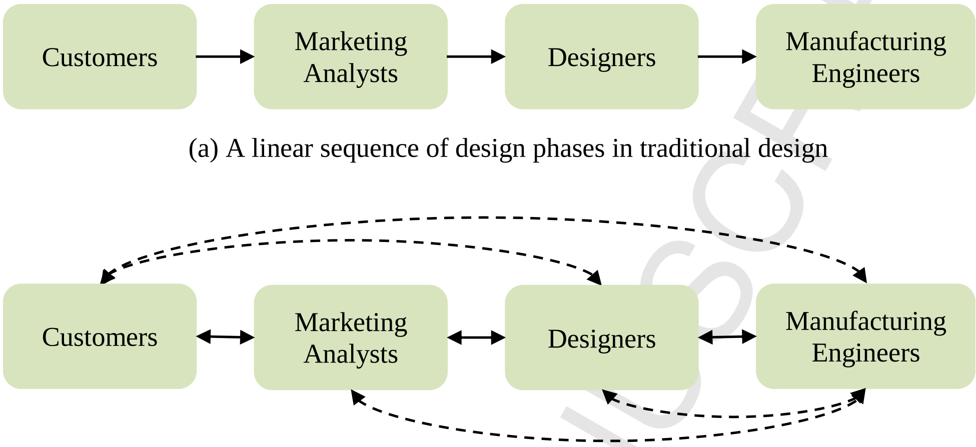
As previously stated, in the proposed computing architecture, multi-tenancy enables a single instance of the application software to serve multiple tenants. To share computing and IT resources in cloud

computing, multi-tenancy is the most fundamentally used technology for its security and cost efficiency. To provide an interface such as social media and crowdsourcing platforms between service providers and consumers, the web portal of CBDM systems is developed using Web 2.0 technology and associated application software. To improve the negotiation process between service providers and consumers as well as enhance security and privacy in CBDM systems, a cloud broker (e.g., cloud-based storage and computing brokers) can help users identify, customize, and integrate existing design and manufacturing services. For instance, a cloud broker provides services that allow users to analyze the information and material flow in CBDM systems. Moreover, to develop CBDM systems using the semantic web, ontology mapping provides a common layer from which multiple ontologies could be accessed and hence users can exchange design- and manufacturing-related information in a semantically sound manner. In addition, as shown in the virtual and physical layers in Fig. 1, virtualization can improve the efficiency and availability of computing and IT resources by re-allocating hardware dynamically to applications based on their need. Virtualization enables enterprises to separate engineering software packages, computing resources, and data storage from physical computing hardware as well as to support time and resource sharing.

4.2 Design communication

From a communication perspective, one of the ultimate goals of research on engineering design is to improve communication in the design process. As stated before, the design of any product is an inherently social, technical process. The key issue in improving design communication is the extent to which design engineers fully understand a complex design process, in particular, design tasks that need to be finished, individuals from whom specific information can be accessed, the extent to which acquired information is distorted, and influence of the distorted information on design [40]. In traditional collaborative design settings, communication can be seen as a one-way process with a linear sequence of design phases as shown in Fig. 2 (a). Because of the use of social media in CBD settings, design communication can be improved through multiple information channels (e.g., social network sites and product review sites) in

which information flow can take place in multiple directions as shown in Fig. 2 (b) [41]. For instance, social media allows design engineers to collaborate with customers concurrently by receiving instant feedback from customers.



(a) A linear sequence of design phases in traditional design

(b) A linear sequence of design phases with more information channels in CBD

Fig.2: Design communication

Moreover, traditional computer-aided application tools (e.g., CAD/CAE/CAM) were standalone systems and designed for single user without communicating and collaborating with others [42-44]. In CBD settings, engineering design requires more communication and collaboration within and across organizations on the modeling, analysis, and optimization of a design. As stated in Section 4.1, the use of virtualization and multi-tenancy in CBDM has the potential to allow for simultaneous concurrency in computer-aided design, engineering analysis, and manufacturing tools. Specifically, computer-aided design, engineering analysis, and manufacturing tools in CBDM settings will allow users in a cross-disciplinary design team to simultaneously create and modify design features of a product model. In addition, according to a recent survey [42], to communicate in traditional design settings, design engineers spend an average of 15% of their time at work on the phone and receive 50 emails average per day. Communication tools (e.g., instant messaging, virtual meeting, screen sharing, and social network sites) integrated in computer-aided application tools allow for multiple information transmission channels that can significantly improve productivity.

4.3 Sourcing process

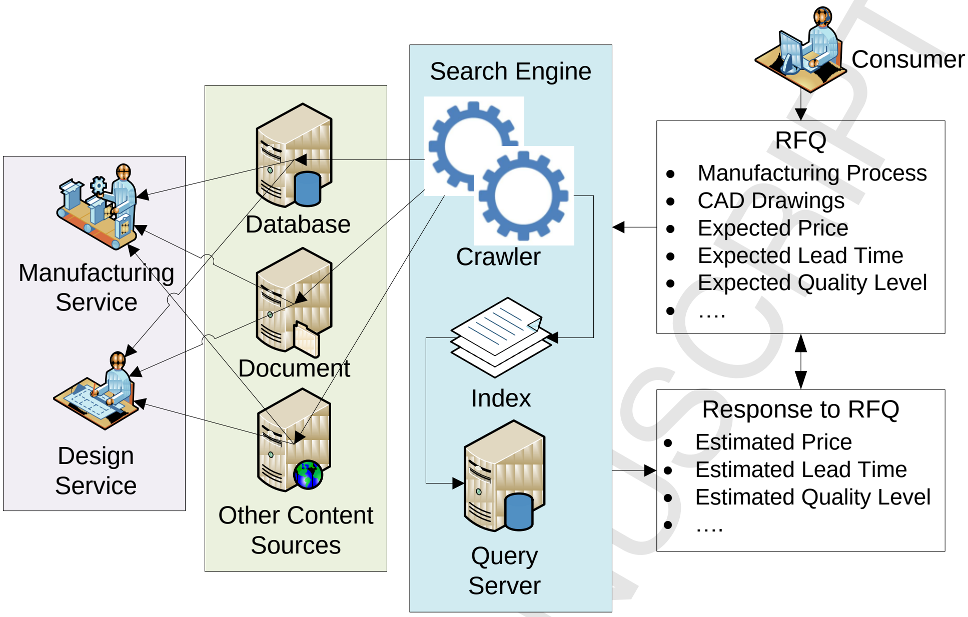


Fig.3: A crowdsourcing process for RFQs in CBDM systems.

From a sourcing process perspective, CBDM can leverage the power of the crowd. For instance, CBDM enables service consumers to quickly and easily locate qualified service providers who offer design and manufacturing services such as CNC machining, injection molding, casting, or 3D printing through a cloud-based sourcing platform. Fig. 3 illustrates the cloud-based sourcing process, which enables consumers to submit requests for quotes (RFQs) to a search engine and receive a list of qualified service providers. The search engine consists of a crawler, indices, and query servers. The crawler gathers manufacturing-related data (e.g., process variables, machine specifications) from databases, document servers, and other content sources, and it stores them in the index. The index ranks these data based on metrics (e.g., price, quality, and geographic location) specified by the users. A query server is the front end of the search engine; it delivers to consumers the results of a search query as a response to the RFQs; the results are based on the specifications such as expected prices, lead times, and quality levels. However, with regard to web- and agent-based design and manufacturing systems, it is not feasible to implement such a computationally expensive sourcing platform that connects service consumers and

providers worldwide. Moreover, in comparison with commercial quoting systems such as Quickparts.com [12] and MFG.com [45], the proposed cloud-based sourcing platform can not only conduct quoting for design and manufacturing services such as rapid prototyping, injection molding, and casting, but also conduct manufacturing and computing resource allocation, and scheduling activities. Further, in contrast with existing 3D printing services where users upload design files and print objects from a single site, CBDM allows users to print their designs at any 3D printer in the cloud rather than at one particular site.

4.4 Information and communication infrastructure

From an information and communication infrastructure perspective, CBDM employs the IoT (e.g., RFID), smart sensor, and wireless devices (e.g., smart phone) to collect real-time design- and manufacturing-related data as shown in Fig. 4.

Fig.4: Information and communication infrastructure in CBDM systems.

The essence of IoT and embedded sensors is to capture events (e.g., inventory level), to represent physical objects (e.g., machine tools) in digital form, and finally to connect machines with people. For instance, IoT allows engineers to have access to data such as machine utilization, equipment conditions, and the percentage of defective products from any location. With the big data generated by the IoT-related

devices, engineers may apply big data analytics for forecasting, proactive maintenance, and automation. However, such seamless connections cannot be provided in web- and agent-based design and manufacturing systems because of their limited data acquisition and computing capabilities.

4.5 Programming model

From a programming model perspective, MapReduce, a parallel programming model, enables CBDM systems to process large data sets which web- and agent-based manufacturing systems are not able to deal with. One of the most well-known open source implementations of the MapReduce model is Hadoop. Similar to other parallel programming models, Hadoop divides computationally extensive tasks into small fragments of work, and each work unit is processed on a computer node in a Hadoop cluster [46]. The MapReduce framework is implemented through two core processes named Map and Reduce. Specifically, in a Map process, a master node receives an input task, divides it into smaller sub-tasks, and distributes them to worker nodes. The worker nodes process the smaller sub-tasks, and send the answer back to the master node. In a Reduce process, a master node receives the answers of all the sub-tasks and combines them to generate the result of the original task. Such a parallel programming model enables CBDM to handle big data generated in design and manufacturing.

4.6 Data storage

From a data storage perspective, with regard to web- and agent-based design and manufacturing, product-related data are stored at designated servers, and users know where these data are as well as who is providing them. However, with regard to CBDM, networked enterprise data are stored not only on users' computers, but also in virtualized data centers that are generally hosted by third parties (see the virtual and physical layers in Fig. 1). Physically, these data may span across multiple servers. In other words, the users may neither exactly know who the service providers are nor where the data are stored. However, the data may be accessed through a web service application programming interface (API) or a web browser. The advantages of cloud-based data storage are: (1) cloud-based data storage provides users with ubiquitous access to a broad range of data stored in the networked servers via a web service

interface; (2) data storage can easily scale up and down as needed on a self-service basis; (3) users are only charged for the storage they actually use in the cloud.

4.7 Business model

From a business model perspective, the significant difference between CBDM and web- and agent-based design and manufacturing is that CBDM involves new business models; but web- and agent-based design and manufacturing paradigms do not. That is, CBDM does not simply provide new technologies; it also involves how design and manufacturing services can be delivered (e.g., IaaS, PaaS, HaaS, and SaaS), how services can be deployed (e.g., private cloud, public cloud and hybrid cloud), and how services can be paid for (i.e., pay-per-use). For example, a key driver of CBDM is the pay-per-use model that has the potential to reduce up-front investments on IT and manufacturing infrastructure for small- and medium-sized enterprises (SMEs). Instead of purchasing manufacturing equipment and software licenses, CBDM users can pay a periodic subscription or utilization fee with minimal upfront costs. Likewise, scalability and elasticity allow users to avoid over purchase of computing and manufacturing capacities.

5. Cloud-based design and manufacturing example scenario

In this section, we present an idealized design and manufacturing scenario in a hypothetical CBDM setting based on currently existing and potentially new cloud-based service offerings. The example scenario is meant to help clarify our vision of CBDM and demonstrate its potential value.

In this scenario, the design task is to develop a next-generation smart delivery product, technically called unmanned aerial vehicles (also referred to as drones as shown in Fig. 5), that can deliver packages from a distribution center to customers faster and at a reasonable price. The design brief is as follows: "The Federal Aviation Administration (FAA) currently has strict regulations for drones. In five years or so, the FAA will address current and future policies, regulations, technologies, and procedures related to the commercial use of drones in the United States. The design task is to conceptualize, design, and prototype a product that can carry a package up to 10 pounds, deliver it in 20 miles in radius within an

hour." Fig. 5 shows the hypothetic scenario for developing the next-generation smart delivery drone using CBDM. More technical details about the example scenario will be described in the following sections.

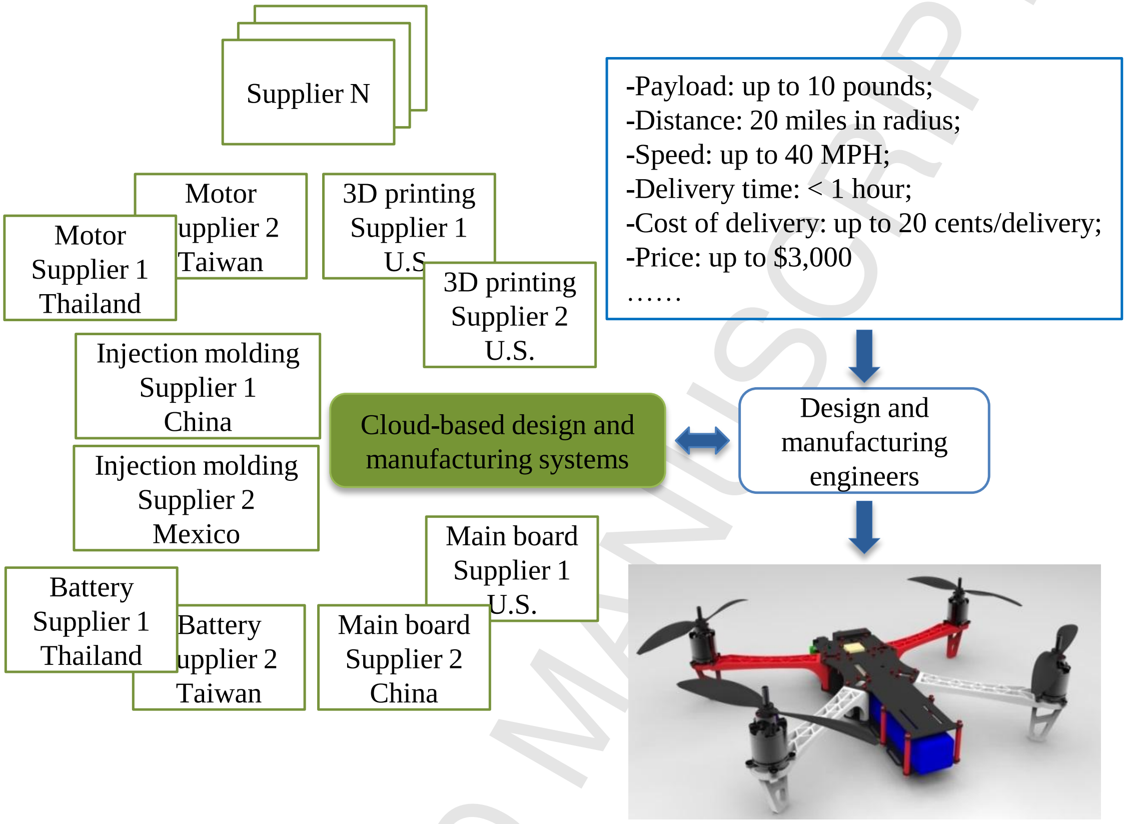


Fig.5: Cloud-based design and manufacturing for drones.

5.1 CBDM system architecture

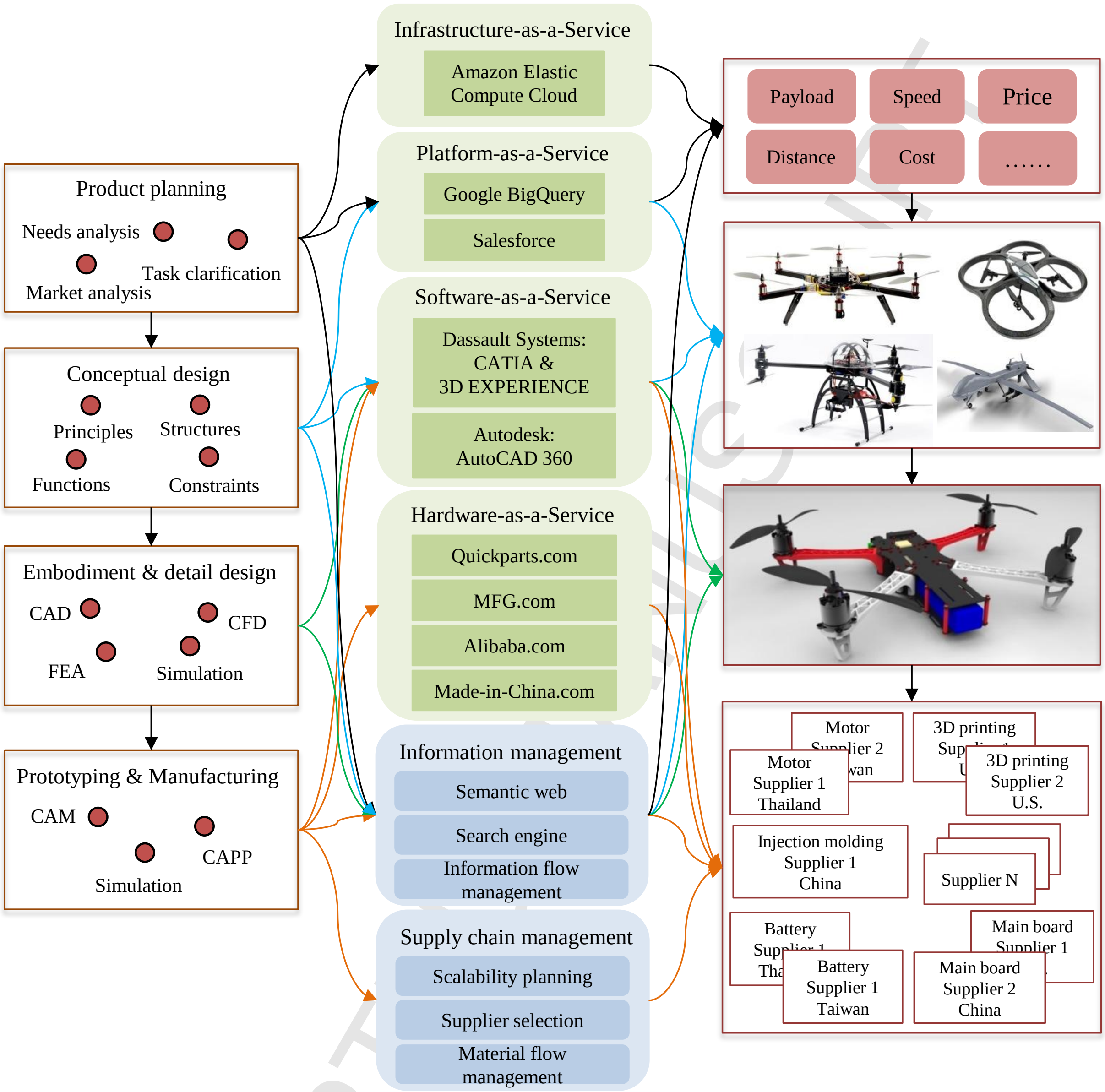


Fig.6: CBDM system architecture (the color of the arrows represents different development stage).

In this section, we present how the integration of existing and potentially new services and technologies may enhance the drone development process. We propose the system architecture of CBDM as shown in Fig. 6 to illustrate the service models (i.e., IaaS, PaaS, HaaS, and SaaS), the existing and potentially new service providers, and the delivery drone development process as an example. Specifically, in the product planning stage, the team analyzes customer needs, the market and clarifies

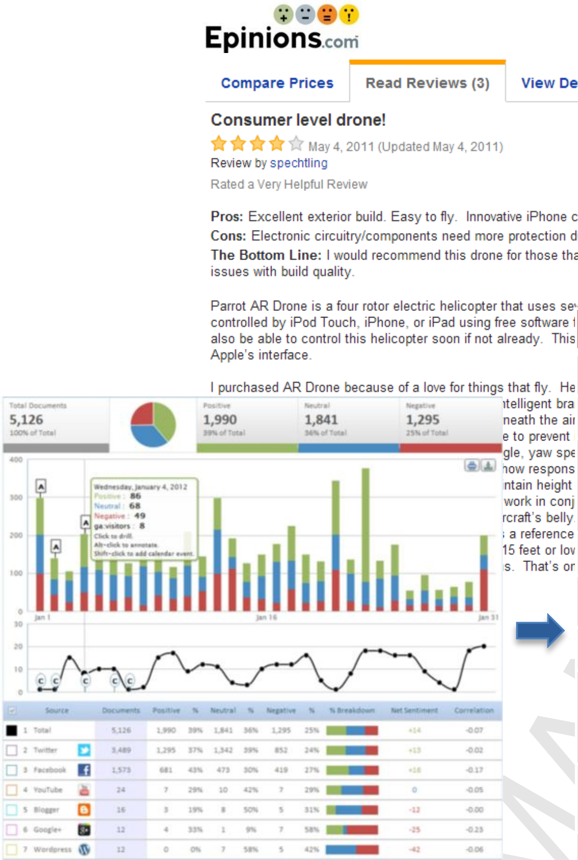
development tasks using IaaS and PaaS provided by Amazon Elastic Compute Cloud, Google BigQuery, and Salesforce. For instance, Amazon allows the team to store large datasets collected from Epinions and Social.com in the cloud-based storage. Google BigQuery and Salesforce.com allow the team to process these massively large datasets. Through the IaaS and PaaS, the team generates design requirements on payload, distance, speed, delivery time and cost, price, degree of autonomy, navigation, design lifetime, and so on more effectively and efficiently. In the conceptual design stage, based on these design requirements, the team proposes function structures, working principles, engineering and economic constraints using PaaS and SaaS. For instance, Autodesk, the provider of SaaS, allows the team to capture drone design concepts digitally and quickly create 3D concept models. Dassault Systemes, the provider of both PaaS and SaaS, allows the team to build custom social media (e.g., wikis and online forum) for enhancing design ideation and sharing design experience. Through the PaaS and SaaS, the team proposes four design concepts: HexaCopter, Quadcopter, Tricopter, and Wing drones as shown in Fig. 6. In the embodiment and detail design stages, based on the proposed design concepts, the team develops preliminary and definitive layouts using CAx application tools (e.g., CAD, FEA, and CFD) using SaaS. For instance, both Dassault Systemes and Autodesk allow the team to have access to CAD drawing files, to perform computational fluid dynamics (CFD) and finite element analysis (FEA) simulations for the drone design using browsers on a pay-per-use basis. In the prototyping and manufacturing stages, the team develops a prototype of the drone and manufacturing process plans for mass production using SaaS and HaaS. For instance, Quickparts.com, MFG.com, Alibaba.com and Made-in-China.com, the providers of HaaS, allow the team to source manufacturing tasks to qualified suppliers and manufacturers using the instant quoting engine. Quickparts also allows the team to perform manufacturability analysis for the drone parts before 3D printing.

In addition to the existing cloud-based commercial software systems and services, some new modules of the CBDM system are needed including information and supply chain management. As shown in Fig. 6, the cloud-based information management module allows the team to exchange and share drone development-related information throughout the drone development process. Semantic web-based design

and manufacturing knowledge representation can significantly automate the design and manufacturing processes and increase productivity using the machine-readable knowledge representation scheme. The semantic search engine allows design and manufacturing engineers to improve search accuracy by using semantics rather than using ranking algorithms. The information management module also allows engineers to capture the correct information from the right individual based on social network analysis (SNA). This unique feature can significantly improve communication and collaboration in the design and manufacturing process. Moreover, the cloud-based supply chain management module allows for manufacturing capacity scalability planning and control by simulating the material flow in the CBDM process and optimizing supplier selection. In Sections 5.2 and 5.3, we will highlight the benefits of developing the drone using a CBDM system from multiple perspectives in more detail.

5.2 Cloud-based design

From a requirements elicitation perspective, CBD allows design engineers to conduct market research more effectively and efficiently through social media. Specifically, they can use business-targeted market research platforms such as HootSuite [47], Epinions [48], and Salesforce.com [49] to collect customer feedback and responses on existing and new features of drones. For instance, HootSuite allows the design team to collect massive customer feedback and reviews across most of the major social networks such as Twitter, Facebook, Google plus as well as social marketing sites such as Foursquare [50]. Similarly, social media-based market research platforms (e.g., social.com, radian 6, and buddy media) provided by Salesforce allow the design team to identify lead users for design innovation by creating engaging Facebook tabs rather than by performing survey of large user populations. After collecting these data from social media, design engineers can elicit design requirements and customer preference using cloud-based big data analytics tools such as Google BigQuery [51]. For instance, Google BigQuery allows for processing these massively large datasets using the MapReduce framework, a parallel and distributed programming model. As shown in Fig. 7, these data analytics generated by Google BigQuery allow design engineers to derive the functional requirements of the drone more effectively and efficiently.



Category	Requirements
Payload	Up to 10 pounds
Distance	20 miles in radius
Speed	Up to 40 miles per hour, 25 miles per hour average
Delivery time	Within an hour
Cost of delivery	20 cents per delivery
Price	Up to $3,000
Degree of autonomy	Optimal path planning; optimal task allocation and scheduling;
Mechanical function	Grab and release
Navigation	Autopilot and GPS navigation
Design lifetime	5 years

Fig.7: Requirements elicitation based on customer reviews.

From a conceptual design perspective, cloud-based crowdsourcing platforms allow the design team to solicit new design ideas from more sources such as customers, users, and hobbyists, thereby enhancing ideation for product innovation. For example, the design team can launch such a cloud-based crowdsourcing platform, similar to Local Motors' open-source platform [52], to source collaborative design ideas from an online community of designers, engineers, and fabricators. Such a crowdsourcing platform can help the design team generate more innovative drone design concepts as shown in Fig. 8.

Fig.8: Various design concepts for delivery drones [60-62].

From a design communication perspective, cloud-based information management tools allow for enhanced information flow management that can significantly improve design productivity. From this aspect, collaborative design can be modeled as an information-driven process among design activities. Participants in collaborative design can be viewed as a social network in which design-related information are transmitted from one to another. In this context, having access to the right design information from the right designer – the correct product specifications and the correct version of a drawing or model – is imperative for collaborative design. Through social network analysis (SNA), CBD has the potential to help design engineers capture the correct design information from the right individual in an escalating virtual and social environment. The graph theory and data mining tools in SNA allow for visualizing information flow in the drone design network, detecting groups of design engineers with common design interests and activities while design activities are being conducted. For instance, Fig. 9 illustrates that multiple design sub-groups (e.g., hardware group for frame, manipulator, propeller design and software group for navigation and motion control systems) are detected while the drone is being designed. These data mining and visualization technologies used in CBD have the potential to significantly increase the productivity for the drone design process by allowing design engineers to search for the right design information from the right designer.

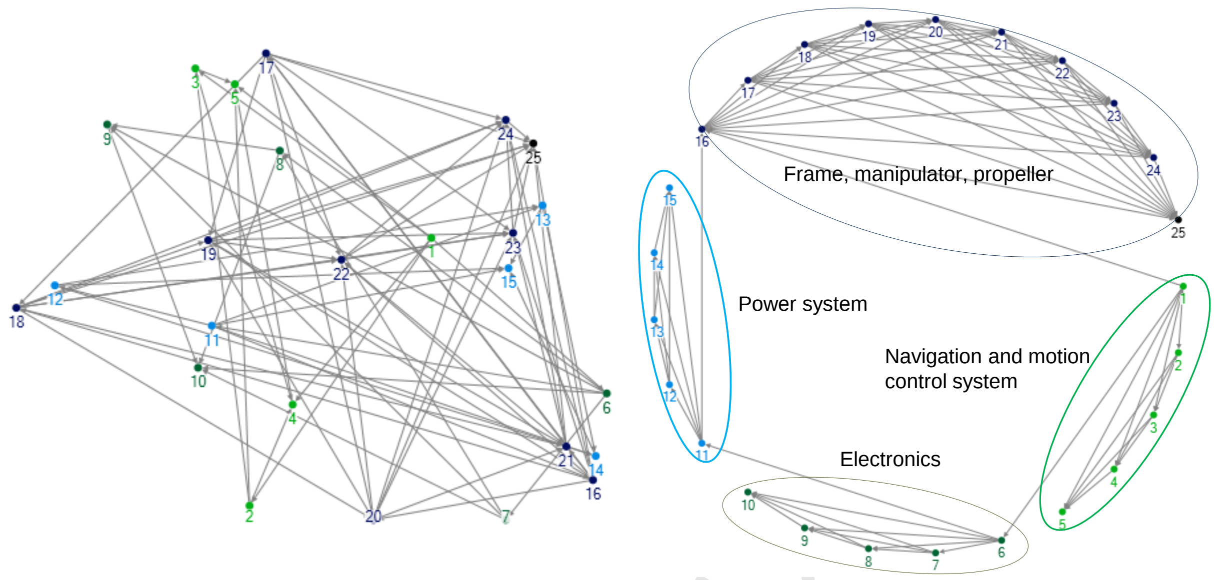


Fig.9: Information flow visualization and community detection [41].

From a computer-aided design perspective, the traditional collaborative design process is typically expensive because it requires substantial computing resources, data consistency, transparent communication and seamless information sharing. As stated before, web- and agent-based collaborative design platforms enable authorized users in geographically different locations to have access to design-related data such as CAD drawing files stored at designated servers and to perform computationally extensive simulation and analysis simultaneously and collaboratively through the client-server architecture. CBD has the potential to allow the distributed design team to conduct these design activities more cost-effectively and efficiently by using cloud-based CAx software such as CATIA V6 [53] and AutoCAD 360 [6]. For instance, CATIA V6 provides the design team with a flexible subscription pricing model, namely pay-per-use, without upfront investments in CAx software. Specifically, the 3DEXPERIENCE cloud-based platform [53] enables the design team to perform computing-intensive computational fluid dynamics (CFD) simulation and finite element analysis (FEA) for the drone design by utilizing high performance and highly scalable computing resources provided by the Amazon Elastic Compute Cloud (Amazon EC2). Virtualization and multi-tenancy technologies used in CBD allow design

engineers to simultaneously create and modify design features of a drone CAD model while ensuring data consistency.

5.3 Cloud-based manufacturing

After the detail design phase is finished, the design team needs to build a prototype in a CBM setting. Fig. 10 shows a simplified drone model with a few labeled parts.

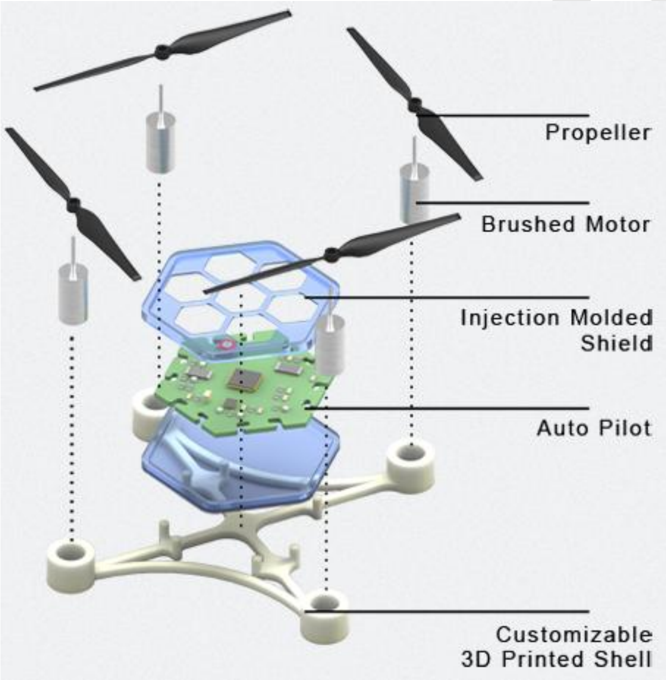


Fig.10: Build a simplified drone model using 3D printing and injection molding [54].

Fig.11: Build the propeller of the drone using 3D printing [63].

Some of the mechanical parts such as the propellers and frame of the drone can be 3D printed (see Fig. 11). Others such as the shield can be injection molded.

From a rapid prototyping perspective, CBM allows the design team to build the prototype more efficiently and cost effectively without large upfront investment in manufacturing equipment. The design team can manufacture the major mechanical components of the drone through cloud-based sourcing platforms (Quickparts, MFG.com, Alibaba.com [55], and i.materialise [56]). For instance, Quickparts connects the design team to hundreds of 3D printing service providers through an instant quoting engine. Quickparts enables design engineers to upload their CAD files of the drone design created by CATIA and SolidWorks, to perform geometric and printability analysis, and finally to receive a list of qualified service providers instantly. The geometric and manufacturability analysis significantly improves the design for manufacturability process and increases manufacturing efficiency and productivity. In addition to 3D printing, MFG.com allows the design team to discover global suppliers who deliver a variety of manufacturing services such as injection molding, casting, and machining for manufacturing some

components of the drone. Moreover, Alibaba.com [55] and Made-in-China.com [57] allow the team to discover suppliers who provide electrical and electronics components (e.g., motion control board, camera, pressure, temperature and speed sensors, and autopilot management unit). Sourcing manufacturing tasks and electronics components to service providers not only allows the design team to save upfront investment in 3D printers and injection molding machines but also allows them to focus on design innovation.

From a manufacturing automation perspective, the cyber-infrastructure of CBM along with semantic web-based manufacturing knowledge representation has the potential to automate manufacturing processes. Specifically, the machine-readable knowledge representation scheme, called web service description language (WSDL), and universal description discovery and integration (UDDI) allow manufacturing service providers to publish their manufacturing services in a machine-readable language. Further, the formal representation of manufacturing resources enables the automatic retrieval of the required manufacturing services based on the semantic matchmaking of required and published manufacturing service specifications [58]. For instance, in this example scenario, CBM allows the team to automatically retrieve a list of 3D printers that are capable of building the propellers based on the published manufacturing specifications such as build time and costs. Fig. 11 shows some of the manufacturing specifications including build material, maximum model dimension, and layer resolution.

From a manufacturing capacity scalability perspective, CBM allows the development team to leverage more cost-effective manufacturing services from global manufacturing suppliers (see Fig. 5) and to rapidly scale up and down manufacturing capacity. In this example scenario, after considerable testing and prototyping, if the drone is deemed commercially viable, the team will introduce the drone into the market. In the introduction stage, customers are few and sales are low. If the drone is popular with consumers, then market demand will start to increase and sales will start to rise. At this stage, the team will have to scale manufacturing capacity and put the drone into mass production. To achieve this goal, for instance, the frame and propellers can be sourced to 3D printing suppliers in U.S.; the shield can be sourced to injection molding suppliers in Mexico; the battery can be sourced suppliers in Thailand; some

of the electronic components such as the main board can be sourced to China. Moreover, manufacturing capacity can be rapidly scaled up when needed, because the team can almost always find a list of qualified service providers whose manufacturing capacity is not fully utilized using the aforementioned cloud-based global sourcing platforms. Even if most manufacturing service providers are running at their full capacity, in order to make more profits or receive larger orders, these service providers may still prioritize manufacturing tasks and reallocate their manufacturing capacity to more profitable businesses.

From a manufacturing supply chain perspective, CBM has the potential to optimize complex material flow in the cloud-based sourcing process, thereby increasing manufacturing productivity [59]. As stated before, CBM allows for rapid manufacturing capacity scalability by sourcing manufacturing tasks to global suppliers. Scaling up and down manufacturing capacity for the drone requires detecting manufacturing bottlenecks and optimizing manufacturing supply chain. To achieve this goal, material flow that transforms raw material to parts, to sub-assembly, to assembly, and finally to end-products between service providers and consumers needs to be planned and controlled. To systematically plan and control the material flow in the manufacturing supply chain, a third-party entity, also referred to as a CBM broker, provide approaches that allow for modeling, analyzing, and optimizing the material flow prior to implementation. By simulating manufacturing processes, the team observes that building the propellers and frame and transporting them back to the assembly plant take longer time than average cycle time, thereby becoming manufacturing bottlenecks. Through the simulation, the team can select optimal suppliers for the propellers and frame by taking manufacturing and transportation times and costs into account.

The above idealized and simplified example scenario in a hypothetical CBDM setting illustrates how the proposed CBDM paradigm has the potential to enhance the product realization process from multiple perspectives. In particular, we demonstrate that CBDM has the potential to significantly enhance design innovation and increase design efficiency, to reduce prototyping costs and enhance design for manufacturability, to increase digital manufacturing productivity, and to enable manufacturing capacity scalability in comparison with traditional collaborative design distributed manufacturing paradigms.

6. Conclusion

In this paper, we discussed and compare the existing definitions for CBDM, identified common key characteristics, defined a requirements checklist that any idealized CBDM system should satisfy, and compared CBDM to other relevant but more traditional collaborative design and distributed manufacturing systems from a number of perspectives. Specifically, CBDM is characterized by scalability, agility, high performance and affordable computing, networked environments, ubiquitous access, self-service, big data, search engine, social media, real-time quoting, pay-per-use, resource pooling, virtualization, multi-tenancy, crowdsourcing, IaaS, PaaS, HaaS, and SaaS. Thus far, a few prototype systems achieved some functions in the requirement checklist; however, none of the existing systems satisfies all the requirements that we defined. The requirements checklist could serve as a benchmark for developing future CBDM systems. Moreover, CBDM is distinguished from web- and agent-based approaches from the perspectives of computing architecture, design communication, sourcing process, information and communication infrastructure, programming model, data storage, and business model. Further, we present an idealized design and manufacturing scenario in a hypothetical CBDM setting based on currently existing and potentially new cloud-based service offerings. The example scenario, the development of a smart delivery drone, is meant to help clarify our vision of CBDM and demonstrate its potential value.

Finally, in response to the question initially posed, whether or not cloud-based design and manufacturing is a new, emerging paradigm in digital manufacturing and design innovation, or just old wine in new bottles, we concluded that cloud-based design and manufacturing can be considered as a new, emerging paradigm that will revolutionize digital manufacturing and design innovation, although cloud-based design and manufacturing is the result of evolution and adoption of existing technologies and design and manufacturing paradigms.

Meanwhile, the following questions remain open for investigation:

- What impact can future and emerging technologies have on CBDM?
- What types of design and manufacturing services are suitable to move to the cloud?

- What types of companies are suitable to adopt CBDM?
- What strategies or business models should be used by service providers and consumers?

To bridge the gap between currently existing technologies, services, infrastructures and our vision of CBDM, it is worthwhile to discuss how future and emerging technologies such as cyber-physical systems (CPS), the internet of things (IoT), and big data can help achieve and improve CBDM:

- CPS is expected to play a major role in the design and development of future CBDM systems. Advances in CPS research can help integrate design- and manufacturing-related knowledge and principles, connect both cyber and physical components, and enhance the interaction among complex physical machinery, networked sensors, and engineering software. In particular, future CPS that exceed today's levels of autonomy, functionality, reliability, and cyber security will allows for improved connectivity, adaptability, flexibility, and scalability in CBDM [66]. Moreover, because future CBDM systems will integrate heterogeneous distributed computational modeling techniques and simulation tools, improved interoperability in CPS can ensure that CBDM systems have the capability to seamlessly communicate, execute computer programs, and transfer data among various functional units as well as to perform automatic logical inference and knowledge discovery [67]. Meanwhile, cyber-security is a critical aspect of CBDM at many levels, including system integrity, data security, intellectual property, and privacy. To address rapidly evolving cyber and physical threats, it is crucial to develop formal trust models between actors (e.g., service consumers and providers) in CBDM systems and quantitative approaches to CPS vulnerability assessments.
- In addition, IoT is another key enabling technology to improve manufacturing automation, supply chain management, remote maintenance and diagnostics in the future development and implementation of CBDM. Specifically, because IoT is characterized by ubiquitous computing (e.g., embedded smart sensors and actuators) and pervasive sensing technologies (e.g., Radio-Frequency Identification tags), it has the potential to automate manufacturing processes by

connecting humans, machines, manufacturing processes, and design- and manufacturing-related massive data sets. In addition, future advances in wireless sensor networks, pervasive remote tracking/monitoring, and standardization of communications protocols will allow for effective and efficient machine to machine, machine to infrastructure, machine to environment, human to human, and human to machine communications from anywhere at any time. For example, real-time tracking/monitoring data will enable CBDM systems to track and trace specific objects, to monitor and synchronize material flow in manufacturing, and eventually increase the productivity and efficiency of manufacturing supply chain. Real-time performance data will help achieve cloud-based remote maintenance and diagnostics.

- Moreover, because the manufacturing sector generates a great deal of text and numerical data in product development processes, future high performance algorithms and open source platforms for big data search, mining, and processing will significantly impact on design innovation, manufacturing intelligence, cost reduction, scalability, and efficiency in CBDM. For example, semantic-based big data analytics can help forecast sales volumes based on various market and economic variables and determine what key measurable manufacturing parameters most influence customer satisfaction [68]. Future advances in pattern recognition, sentiment analysis, and recommendation systems for big data can help designers extract crucial customer needs from the increasing volume of customer- and user-generated data to refine existing designs and develop new products.

REFERENCES

[1] Foster, I., Zhao, Y., Raicu, I., & Lu, S. (2008). Cloud Computing and Grid Computing 360-Degree Compared. Grid Computing Environments Workshop, Austin.

[2] Putnik, G., Sluga, A., ElMaraghy, H., Teti, R., Koren, Y., Tolio, T., & Hon, B. (2013). Scalability in manufacturing systems design and operation: State-of-the-art and future developments roadmap. CIRP Annals-Manufacturing Technology.

[3] Wu, D., Thames, J.L., Rosen, D.W., & Schaefer, D. (2013). Enhancing the Product Realization Process with Cloud-Based Design and Manufacturing Systems. Transactions of the ASME, Journal of Computing and Information Science in Engineering, 13(4): 041004-041004-14. Doi: 10.1115/1.4025257.

[4] Wu, D., Rosen, D.W., & Schaefer, D. (2014). Cloud-Based Design and Manufacturing: Status and Promise. In: Schaefer, D. (Ed.): Cloud-Based Design and Manufacturing: A Service-Oriented Product Development Paradigm for the 21st Century, Springer, London, UK, ISBN 978-3-319-07397-2, 282pp.

[5] Autodesk. (2014). Available from http://www.123dapp.com/.

[6] Autodesk. (2014). Available from https://www.autocad360.com/.

[7] 100kgarages.com. (2014). Available from http://100kgarages.com/.

[8] Wu, D., Greer, M.J., Rosen, D.W., & Schaefer, D. (2013). Cloud Manufacturing: Strategic Vision and State-of-the-Art. Journal of Manufacturing Systems.

[9] Wu, D., Thames, J.L., Rosen, D.W., & Schaefer, D. (2012). Towards a Cloud-Based Design and Manufacturing Paradigm: Looking Backward, Looking Forward. Proceedings of the ASME 2012 International Design Engineering Technical Conference & Computers and Information in Engineering Conference (IDETC/CIE12), Paper Number: DETC2012-70780, Chicago, U.S.

[10] Li, B. H., Zhang, L., Wang, S. L., Tao, F., Cao, J. W., Jiang, X. D., Song, X., & Chai, X. D. (2010). Cloud manufacturing: a new service-oriented networked manufacturing model. Computer Integrated Manufacturing Systems, 16(1), 1-7.

[11] Xu, X. (2012). From cloud computing to cloud manufacturing. Robotics and Computer-Integrated Manufacturing, 28(1), 75-86.

[12] Quickparts. (2014). Available from http://www.3dsystems.com/quickparts/about/quickquote

[13] Livesource. (2014). Available from http://www.livesource.com/

[14] 3D Hubs. (2014). Available from http://www.forbes.com/sites/jenniferhicks/2013/08/27/3d-hubs-crowdsources-3d-printing/.

[15] Netfabb. (2014). Available from http://cloud.netfabb.com/

[16] Pahl, G., & Beitz, W. (1984). Engineering design (Vol. 984). K. Wallace (Ed.). London: Design Council.

[17] Ulrich, K. T., & Eppinger, S. D. (1995). Product design and development (Vol. 384). New York: McGraw-Hill.

[18] Hicks, B. J., Culley, S. J., & McMahon, C. A. (2007). The barriers to improving information management in engineering organizations. In International Conference on Engineering Design ICED 07.

[19] Zheng, L. Y., Liu, Q., & McMahon, C. A. (2010). Integration of process FMEA with product and process design based on key characteristics. In Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology (pp. 1673-1686). Springer Berlin Heidelberg.

[20] Ding, L., Davies, D., & McMahon, C. A. (2009). The integration of lightweight representation and annotation for collaborative design representation. Research in Engineering Design, 20(3), 185-200.

[21] Design world online. (2014). Available from http://www.designworldonline.com/50-years-of-cad/#_

[22] Sutherland, I. E. (1964). Sketch pad a man-machine graphical communication system. In Proceedings of the SHARE design automation workshop (pp. 6-329). ACM.

[23] Li, W. D., Lu, W. F., Fuh, J. Y., & Wong, Y. S. (2005). Collaborative computer-aided design – research and development status. Computer-Aided Design, 37(9), 931-940.

[24] Wang, L., Shen, W., Xie, H., Neelamkavil, J., & Pardasani, A. (2002). Collaborative conceptual design – state of the art and future trends. Computer-Aided Design, 34(13), 981-996.

[25] Fuh, J. Y., & Li, W. D. (2005). Advances in collaborative CAD: the-state-of-the art. Computer-Aided Design, 37(5), 571-581.

[26] Piller, F., Vossen, A., & Ihl, C. (2012). From social media to social product development: the impact of social media on co-creation of innovation. Unternehmung, 66(1), 7.

[27] Schaefer, D. (Ed.). (2014). Product development in the socio-sphere: Game changing paradigms for 21st century breakthrough product development and innovation. Springer, London, UK, ISBN 978-3-319-07403-0, 235pp.

[28] Tolio, T., Ceglarek, D., ElMaraghy, H. A., Fischer, A., Hu, S. J., Laperrière, L., Newman, S.T., & Váncza, J. (2010). SPECIES—Co-evolution of products, processes and production systems. CIRP Annals-Manufacturing Technology, 59(2), 672-693.
[29] Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., & Shpitalni, M. (2011). Assembly system design and operations for product variety. CIRP Annals-Manufacturing Technology, 60(2), 715-733.
[30] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., & Van Brussel, H. (1999). Reconfigurable manufacturing systems. CIRP Annals-Manufacturing Technology, 48(2), 527-540.
[31] ElMaraghy, H. A. (2005). Flexible and reconfigurable manufacturing systems paradigms. International Journal of Flexible Manufacturing Systems, 17(4), 261-276.
[32] Wang L., Shen W., & Lang S. (2004). Wise-ShopFloor: a Web-Based and Sensor-Driven e-Shop Floor, Transactions of the ASME, Journal of Computing and Information Science in Engineering, 4(1), 56-60.
[33] Shen, W., Hao, Q., Yoon, H. J., & Norrie, D. H. (2006). Applications of agent-based systems in intelligent manufacturing: An updated review. Advanced engineering informatics, 20(4), 415-431.
[34] Wang L. & Shen W. (2003). DPP: An Agent-Based Approach for Distributed Process Planning, Journal of Intelligent Manufacturing, 14(5), 429-439.
[35] Monostori, L., Váncza, J., & Kumara, S. R. (2006). Agent-based systems for manufacturing. CIRP Annals-Manufacturing Technology, 55(2), 697-720.
[36] Ren, L., Zhang, L., Tao, F., Zhang, X., Luo, Y., & Zhang, Y. (2012). A methodology towards virtualization-based high performance simulation platform supporting multidisciplinary design of complex products. Enterprise Information Systems, 6(3), 267-290.
[37] Marozzo, F., Talia, D., & Trunfio, P. (2012). P2P-MapReduce: Parallel data processing in dynamic Cloud environments. Journal of Computer and System Sciences, 78(5), 1382-1402.
[38] Numecent. (2014). Available from http://gfxspeak.com/2013/07/19/numecent-launches-native-as-a-service-cloudpaging-platform/.
[39] Chang, X., Rai, R., & Terpenny, J. (2010). Development and utilization of ontologies in design for manufacturing. Journal of Mechanical Design, 132(2), 021009.
[40] Eckert, C., Maier, A., & McMahon, C. (2005). Communication in design. In Design process improvement (pp. 232-261). Springer London.
[41] Wu, D., Schaefer, D., & Rosen, D.W. (2013). Cloud-Based Design and Manufacturing Systems: A Social Network Analysis. International Conference on Engineering Design (ICED13), Seoul, Korea.
[42] Red, E., French, D., Jensen, G., Walker, S. S., & Madsen, P. (2013). Emerging design methods and tools in collaborative product development. Journal of Computing and Information Science in Engineering, 13(3), 031001.
[43] Red, E., Holyoak, V., Jensen, C. G., Marshall, F., Ryskamp, J., & Xu, Y. (2010). ν-CAx: A Research Agenda for Collaborative Computer-Aided Applications. Computer-Aided Design and Applications, 7(3), 387-404.
[44] Hepworth, A., Tew, K., Trent, M., Ricks, D., Jensen, G., & Red, E. (2014), Model consistency and conflict resolution with data preservation in multi-user computer-aided design. Journal of Computing and Information Science in Engineering, 14(2), 021008.
[45] MFG. (2014). Available from http://www.mfg.com/
[46] Dean, J., & Ghemawat, S. (2008). MapReduce: simplified data processing on large clusters. Communications of the ACM, 51(1), 107-113.
[47] Hootsuite. (2014). Available from https://hootsuite.com/
[48] Epinions. (2014). Available from http://www.epinions.com/?sb=1
[49] Salesforce.com. (2014). Available from http://www.salesforce.com/marketing-cloud/overview/
[50] Foursquare. (2014). Available from https://foursquare.com/
[51] Google. (2014). Available from https://developers.google.com/bigquery/

[52] Local Motors. (2014). Available from https://localmotors.com/cocreate/
[53] Dassault Systemes. (2014). Available from http://www.3ds.com/products-services/3dexperience/on-cloud/.
[54] Floxbot. (2014). Available from http://flexbot.cc/
[55] Alibaba Group. (2014). Available from http://sourcing.alibaba.com/
[56] i.materialise. (2014). Available http://i.materialise.com/
[57] Made-in-China. (2014). Available from http://www.made-in-china.com/
[58] Yim, S., & Rosen, D.W. (2012). Build time and cost models for additive manufacturing process selection. Proceedings of the ASME 2012 International Design Engineering Technical Conference & Computers and Information in Engineering Conference (IDETC/CIE12), Paper Number: DETC2012-70940, Chicago, U.S.
[59] Wu, D., Rosen, D.W., & Schaefer, D. (2014). Modeling and analyzing the material flow of crowdsourcing processes in loud-based manufacturing systems using stochastic petri nets. Proceedings of the ASME 2014 International Manufacturing Science and Engineering Conference (MSEC14), Paper Number: MSEC2014-3907, Detroit, Michigan, U.S.
[60] Parrot. (2014). Available from http://ardrone2.parrot.com/
[61] 3D Robotics. (2014). Available from http://3drobotics.com/
[62] Amazon. (2014). Available from http://www.amazon.com/b?node=8037720011
[63] Stratasys. (2014). Available from http://www.stratasys.com
[64] Fan, L. Q., Senthil Kumar, A., Jagdish, B. N., & Bok, S. H. (2008). Development of a distributed collaborative design framework within peer-to-peer environment. Computer-Aided Design, 40(9), 891-904.
[65] Mahdjoub, M., Monticolo, D., Gomes, S., & Sagot, J. C. (2010). A collaborative Design for Usability approach supported by Virtual Reality and a Multi-Agent System embedded in a PLM environment. Computer-Aided Design, 42(5), 402-413.
[66] Baheti, R., & Gill, H. (2011). Cyber-physical systems. The impact of control technology, 161-166.
[67] Colombo, A. W., Bangemann, T., Karnouskos, S., Delsing, S., Stluka, P., Harrison, R., Jammes, F., & Martinez Lastra, J. (2014). Industrial Cloud-Based Cyber-Physical Systems. Springer International Publishing.
[68] Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C., & Byers, A. H. (2011). Big data: The next frontier for innovation, competition and productivity. Technical report, McKinsey Global Institute.

Highlight:

- We present a new paradigm in digital manufacturing and design innovation, namely cloud-based design and manufacturing (CBDM).
- We identify the common key characteristics of CBDM.
- We define a requirement checklist that any idealized CBDM system should satisfy.
- We compare CBDM with other relevant but more traditional collaborative design and distributed manufacturing systems.
- We describe an idealized CBDM application example scenario.